Stochastic Modeling of Plug-In Electric Vehicles' Parking Lot in Smart Multi-Energy System

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Abstract. In this paper the role of Plug-In Electric Vehicles' (PIEVs) parking lot in operating Smart Multi-Energy System (SMES) has been investigated. SMES in this paper has been modeled as a multi-input multi-output model which consists of some storage and energy converters. In the proposed framework, the PIEV's parking lot behaves like an energy storage with selling energy price less than upstream network price and as manageable load when its purchase price is more than upstream network. On the other hand, traffic pattern of PIEVs in parking lot has an uncertain behavior and is modeled based on stochastic approach. In the stochastic model, two branches of scenarios for total state of charge and total capacity of parking lot in each hour are produced. The considered case studies show the effectiveness of the proposed model and the impact of PIEVs' parking lot in operation of SMES elements.

Keywords: Energy hub model, PIEVs' parking lot, stochastic modeling.

1. Introduction

Environmental aspects have been highlighted in development of societies by means of sustainable development. In this regard, sustainable energy development is the most important matter to take into account the applicable interaction of preserving the environment with providing the energy requirements [1]. Nowadays, integrated management of energy carriers and other energy related infrastructures (e.g. transportation system) is proposed as one of the approaches to achieve this goal [2].

Many researches have been oriented to model this new decision making environment and to propose management frameworks for Smart Multi-Energy Systems (SMES). Two pioneer models in this area are "energy hub system" and "matrix modeling". Both of the approaches consider the SMES as combination of operation centers (mostly co-generation or tri-generation units) and their interconnectors. Operation centers have been modeled by coupling matrix which converts input energy carriers to the output required energy services [3] and [4]; and Interconnectors transmit energy between operation centers based on energy carriers' physical constraints [5]. References [6] and [7] have modeled the operation framework for operation centers and interconnectors in SMESs. On the other hand, mitigating environmental concerns by electrifying demand of carbon-based energy carriers are another important approach for sustainable development in energy sector.

Plug-In Electric Vehicles (PIEVs) are main tools for electrification in transportation system [8]. They reduce air pollution inside cities by consuming electricity which is supplied by renewable resources and the power plants located far from the cities. Moreover, PIEVs' batteries prepare bulk storage capacity for power system. PIEVs' parking lots are best opportunity for distribution system operators to utilize electric bulk storage facilities in demand side. It should be noted that, if these PIEVs' charge pattern as electric load are not controlled, it can worsen the network operation condition.

Hence, the main goal of this paper is to propose an operation framework for an energy hub which is equipped by PIEVs' parking lot to change the pattern of charging and discharging of PIEVs in parking lots to enhance the operation flexibility of system.

In [9] a single Plug-in Hybrid Electric Vehicle (PHEV) has been modeled as independent energy hub. Furthermore, [10] investigated the role of PHEVs as controllable loads in energy hub system operation and [11] utilized charging of PHEVs in SMES as flexible load for employing ancillary services (load frequency control) in energy market. However, PIEVs' parking lot has not been considered as the element of energy hub before the present paper.

In this paper, the PIEVs' parking lot in a smart energy hub is modeled as stochastic energy storage. The energy hub operator receives gas and electricity from upstream network and delivers energy services to the customers. Hence, energy hub consists of CHP unit, auxiliary boiler, heat storage and a PIEV's parking lot. In such a system, behavior of PIEV's parking lot follows uncertainties modeled by stochastic method. In the mentioned framework, the patterns of State of Charge (SOC) of connected PIEVs are included in the parking lot. The intention of the energy hub operator is to deliver energy to multi-energy demands in such a way that the benefit of operator being maximized. The numerical results show the role of PIEVs' parking lot for altering energy hub operation pattern and utilizing input energy carriers in better way.

2. Contribution to Collective Awareness Systems

Smartness in energy systems facilitates amendment of new resources in demand side. These new resources introduce interdependency in time and carrier domain which should be considered by integrated models. New highly dependent environment will increase the level of uncertainty in SMES which needs huge amount of information and non-deterministic models for appropriate decision making. Collective awareness system is a brilliant opportunity for SMES managers to openly link these uncertain smart energy centers and enhance their collaboration for the benefit of the enterprise. Although, participation of demand side players, enhance the system performance, imposes system with new human-centered layer. This human layer, authorize main portion of resources in the system e.g. PIEVs and small scale co- or tri-generation units. Collective awareness system will make new framework for implementing these resources and managing the behavior of human layer to act as the SMES managers' desire. In this paper the PIEVs traffic pattern in human layer of SMES system is modeled by stochastic models and their effectiveness on operation of other SMES elements and enhancement of SMES operation flexibility is discussed.

3. Stochastic Modeling of PIEVs' Parking Lot

A stochastic model is developed to quantify behavior patterns of PIEVs at a parking lot. The nominal capacity of parking and the sum of SOC of EVs plugged-in at the parking lot in each hour are the outputs of the model. Capacity of parking lot relies on the number and type of EVs parked at the parking lot. The hourly number of EVs connected to the grid at the parking lot is a probabilistic variable that is related to behavior of EV owners. In this paper, the pattern of available EVs at the parking lot is extracted from the real data that is obtained from number of vehicles parked at parking lots [12].

The energy storage capacity of each EV represents the total energy capacity and it is dependent to the EV class. For example, the energy storage capacity of plug-in hybrid electric vehicles (PHEVs) typically is between 6 kWh and 30 kWh; whereas, the capacity for BEVs varies from 30 to 50 kWh [13]. In [13], twenty four different classes have been considered for EV batteries. The probability distribution of the battery capacities in each EV class occurring in a market is illustrated in Fig. 1.

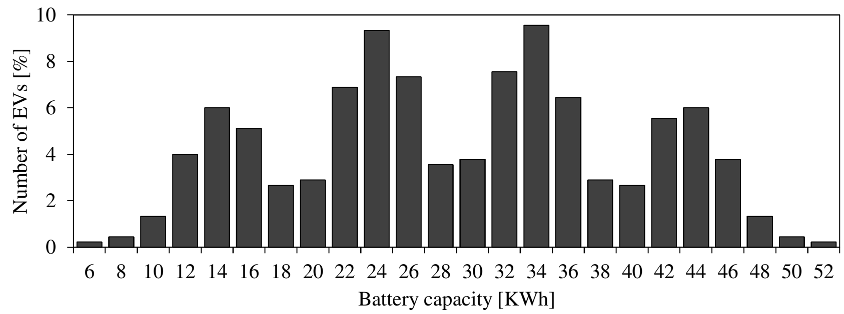

Fig. 1. Distribution of battery capacity.

In order to consider the market share of each EV class, the battery capacity of each class is considered. Taking into account the distribution of EV classes and probability number of EVs at parking lot, the hourly possibility of parking lot capacity is obtained as Fig. 2.

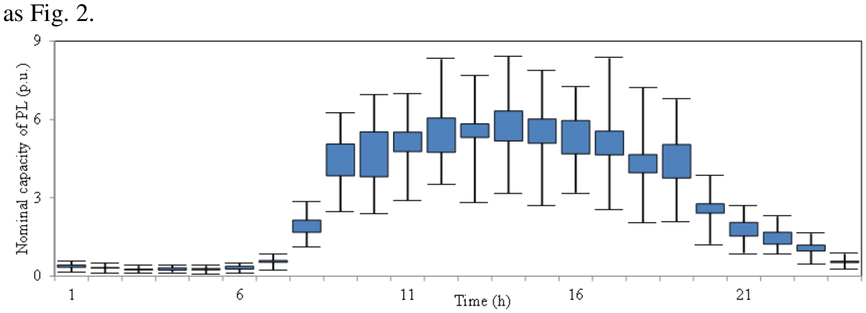

Fig. 2. The hourly nominal capacity of parking lot.

SOC of Parking lot is dependent to number of EVs parked at the parking lot, the type of each EV and the daily driven distance of each EV. The probabilistic traveled distance is applied as a parameter of calculating the SOC of parking lot. The lognormal distribution function is utilized to generate the probabilistic daily traveled distance [14]. The lognormal random variables are generated using standard normal random variable, *N,* and are computed using (1) [15].

$$M_d = \exp(\mu_{md} + \sigma_{md}.N) \quad \mathbf{(1)}$$

where M_d is the daily driven distance. μ_m and σ_m are the lognormal distribution parameters and are calculated from mean and standard variation of M_d based on the historical data, denoted as μ_{md} and σ_{md}, respectively [12]. μ_m and σ_m are calculated based on (2) and (3), respectively.

$$\mu_m = \ln\left(\frac{\mu_{md}^2}{\sqrt{\mu_{md}^2 + \sigma_{md}^2}}\right) \quad \mathbf{(2)}$$

$$\sigma_m = \sqrt{\ln\left(1 + \frac{\sigma_{md}^2}{\mu_{md}^2}\right)} \quad \mathbf{(3)}$$

Vehicles have been used in [12] made an average of 4.2 trips per day, yielding an average daily distance of 39.5 miles. On the other hand, an electric vehicle takes approximately 0.35 kWh to recharge for each mile traveling [12]. On this basis and according to the mentioned above discussion, the hourly SOC of Parking lot can be obtained as illustrated in Fig. 3.

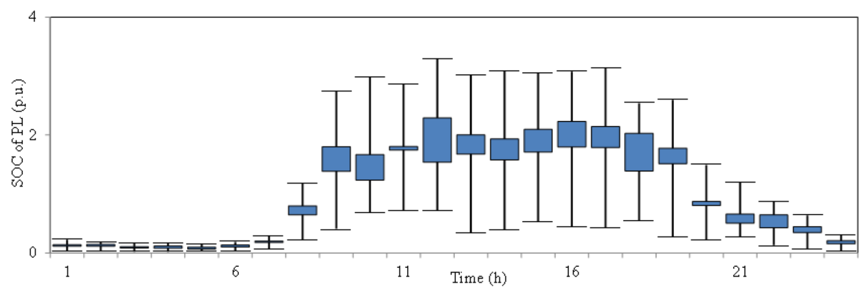

Fig. 3. The hourly SOC of parking lot.

4. Operation Framework of SMES considering PIEVs' Parking Lot

SMES can consist of different elements and distributed energy resources. The focus of this paper is on the PIEVs' parking lot as flexible load in charging mode and large scale electric storage in discharge mode. Operator of SMES supply energy from Electrical Distribution System (EDS) and Gas Distribution Network (GDN) and deliver required service in heat and electricity format to the Multi-Energy Demand (MED).

Fig. 4 shows a typical SMES which consists of Combined Heat and Power (CHP) unit, Auxiliary Boiler (AB), Heat Storage (HS), and PIEVs' Parking Lot (PL).

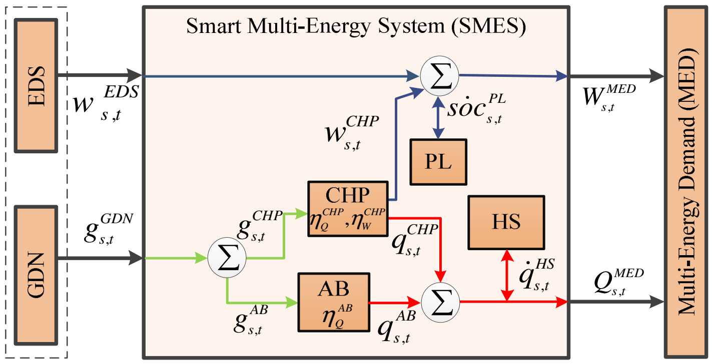

Fig. 4. A typical SMES schematic considering PIEVs' parking lot.

4.1. Matrix Modeling of Smart Multi-Energy System

In depicted SMES schematic the coupling matrix $\mathbf{C}$, converts input energy vector, $\mathbf{p} = \left[w_{s,t}^{EDS} \quad g_{s,t}^{GDN}\right]$, to the required services, $\mathbf{l} = \left[W_t^{MED} \quad Q_t^{MED}\right]$ (eq. (4)).

$$[\mathbf{l}] = [\mathbf{C}].[\mathbf{p}] \tag{4}$$

PIEVs' PL is considered as stochastic storage which can be modeled like HS in coupling matrix by showing the change of its stored energy. In [3], storage modeling in SMES is explained comprehensively. $\mathbf{S}$ is the coupling matrix of the storage, representing how changes in the amount of energy stored will affect the system output. The $\dot{\mathbf{e}}$ vector as indicator of stored energy is added to the input vector and new coupling matrix based on $\mathbf{C}$ and $\mathbf{S}$ is constructed (eq. (5)-(7)).

$$[\mathbf{l}] = [\mathbf{C} \quad -\mathbf{S}].\begin{bmatrix}\mathbf{p} \\ \dot{\mathbf{e}}\end{bmatrix} \tag{5}$$

$$\dot{E}_{\alpha,t} = E_{\alpha,t} - E_{\alpha,t-1} \approx e_\alpha . U_\alpha \tag{6}$$

$$e_\alpha = \begin{cases} \eta_{\alpha,ch}^{Storage}, & if\ U_\alpha \geq 0 \quad \text{(Charge / Standby)} \\ 1/\eta_{\alpha,dis}^{Storage}, & if\ U_\alpha < 0 \quad \text{(Discharge)} \end{cases} \tag{7}$$

Moreover, the detailed matrix model of system is demonstrated in (8):

$$\begin{bmatrix} 1 & v_{G,s,t}^{CHP}.\eta_W^{CHP} & 0 & 1/e_W^{PL} \\ 0 & v_{G,s,t}^{CHP}.\eta_Q^{CHP} + v_{G,s,t}^{AB}.\eta_Q^{AB} & 1/e_Q^{HS} & 0 \end{bmatrix} . \begin{bmatrix} w_{s,t}^{EDS} & g_{s,t}^{GDN} & \dot{q}_{s,t}^{HS} & s\dot{o}c_{s,t}^{PL} \end{bmatrix}^T = \begin{bmatrix} W_t^{MED} \\ Q_t^{MED} \end{bmatrix} \tag{8}$$

4.2. Operational Optimization Problem

The objective of SMES operator is to maximize the benefit from energy trade between customers (MED and PIEVs' owners) and sellers (EDS, GDN and PIEVs' owners) considering the price of energy in peak hours.

Therefore, the objective function of optimization problem includes three terms; first and second terms are the benefit of operator from electricity and gas trade respectively, and the third one is the operator benefit from trading electricity to the PIEVs with contract price (which should be considered PIEV and operator cost, e.g.

installation and battery degradation costs) and manipulation of PIEV's SOC in PL for demand management actions (eq. (9)).

$$\begin{aligned} \textit{Maximizing} \quad & \sum_s \sum_t (w_{s,t}^{EDS} .\pi_{W,t}^{EDS} - W_t^{MED} .\pi_{W,t}^{MED}) + (g_{s,t}^{GDN} .\pi_{Q,t}^{GDN} - Q_t^{MED} .\pi_{Q,t}^{MED}) \\ & + (w_{s,t}^{PL,in} .\pi_{W,t}^{PL,buy} - w_{s,t}^{PL,out} .\pi_{W,t}^{PL,sell}) \end{aligned} \tag{9}$$

Furthermore, due to physical characteristics of SMES's elements, the operation problem faces some constraints:

1) Input energy carriers limitation: EDS and GDN have some limitation for supplying required energy to the SMES. Moreover, the energy flow from EDS and GDN to the SMES is considered unidirectional (eq. (10)).

$$\mathbf{0} \le \mathbf{p} \le \overline{\mathbf{P}} \tag{10}$$

2) CHP operational constraints: CHP unit operates in a predetermined operation zone which is based on its manufacturing characteristics.

$$\underline{W}^{CHP} \le w_{s,t}^{CHP} \le \overline{W}^{CHP} \tag{11}$$

$$\underline{Q}^{CHP} \le q_{s,t}^{CHP} \le \overline{Q}^{CHP} \tag{12}$$

$$\lambda^{CHP} = q_{s,t}^{CHP} / w_{s,t}^{CHP} \tag{13}$$

3) AB operational constraints: AB heat output is constrained by upper and lower limits.

$$\underline{Q}^{AB} \le q_{s,t}^{AB} \le \overline{Q}^{AB} \tag{14}$$

4) HS operational constraints: Interaction between HS and SMES is restricted and also the stored energy in the HS is limited by upper and lower limits.

$$\left| \dot{q}_{s,t}^{HS} \right| \le \gamma_Q^{HS} \tag{15}$$

$$\underline{Q}^{HS} \le q_{s,t}^{HS} \le \overline{Q}^{HS} \tag{16}$$

5) Decision-making variables constraints: Utilizing same service from different energy vectors enhances the operator's degree of freedom. v is the decision making variable which determines this freedom in optimization problem.

$$0 \le v \le 1 \tag{17}$$

$$v_{G,s,t}^{CHP} + v_{G,s,t}^{AB} = 1 \tag{18}$$

4.3. PIEVs' Parking Lot Model in Operation Problem

PIEVs' parking lot behaves as an electrical load in charging mode and as a large scale storage when manage its discharge mode. In proposed model the SMES operator can manipulate the SOC of PIEVs to maximize its profit during operation period. Difference of PL with common storage in modeling is the variation of its capacity which is dependent to the arrival and departure time of PIEVs to the PL. Eq.s (19) and (20), determines the amount of changing in PL's SOC based on PL interaction with SMES and PIEVs' traffic in the parking.

$$s\dot{o}c_{W,s,t}^{PL} = soc_{W,s,t}^{PL} - soc_{W,s,t-1}^{PL} + soc_{W,s,t}^{PL-ar} - soc_{W,s,t}^{PL-dep} \tag{19}$$

$$s\dot{o}c_{W,s,t}^{PL} = l_{W,s,t}^{PL,in} - l_{W,s,t}^{PL,out} \tag{20}$$

In this model, it is assumed that, for arriving PIEVs to the PL in each hour the added SOC by variable $soc_{W,s,t}^{PL-ar}$ is based on the increase in SOC scenarios (eq. (21)) while for departed PIEVs from the PL, the loss in SOC by variable $soc_{W,s,t}^{PL-dep}$ is equal to portion of prior hour SOC considering the decrease in SOC scenarios (eq. (22)).

$$soc_{W,s,t}^{PL-ar} = \begin{cases} soc_{W,s,t}^{PL-Sc} - soc_{W,s,t-1}^{PL-Sc} & if\ soc_{W,s,t}^{PL-Sc} - soc_{W,s,t-1}^{PL-Sc} \geq 0 \\ 0 & if\ soc_{W,s,t}^{PL-Sc} - soc_{W,s,t-1}^{PL-Sc} < 0 \end{cases} \quad \textbf{(21)}$$

$$soc_{W,s,t}^{PL-dep} = \begin{cases} 0 & if\ soc_{W,s,t}^{PL-Sc} - soc_{W,s,t-1}^{PL-Sc} \geq 0 \\ ((soc_{W,s,t-1}^{PL-Sc} - soc_{W,s,t}^{PL-Sc}) / soc_{W,s,t-1}^{PL-Sc}).soc_{W,s,t-1}^{PL} & if\ soc_{W,s,t}^{PL-Sc} - soc_{W,s,t-1}^{PL-Sc} < 0 \end{cases} \quad \textbf{(22)}$$

Furthermore, the interaction amount of PL with SMES is restricted (eq. (23)) and the PL's SOC in each hour is limited by total capacity and minimum required SOC of PIEVs (eq. (24)).

$$\left| s\dot{o}c_{W,s,t}^{PL} \right| \leq \gamma_{W}^{PL} \quad \textbf{(23)}$$

$$0 \leq \underline{SOC}_{W,s,t}^{PL} \leq soc_{W,s,t}^{PL} \leq \overline{SOC}_{W,s,t}^{PL} \leq Cap_{W,s,t}^{PL} \quad \textbf{(24)}$$

5. Numerical Results

SMES operator behaves like energy retailer to maximize its benefit by buying energy from wholesale market and selling it to customers through predetermined tariffs. But SMES operator has some physical asset to arbitrage between energy carriers for increasing its benefit. For considered SMES in this paper, the electricity prices in input and required service in output have been depicted in Fig. 5 and Fig. 6, respectively. Moreover, the GDN gas price is considered as 6 mu/p.u. and delivered heat price to the MED as 7 mu/p.u.

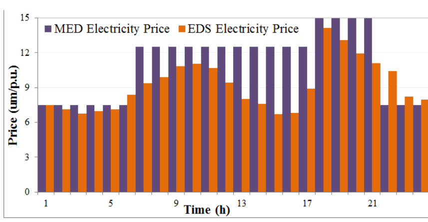

Fig. 5. MED and EDS price data

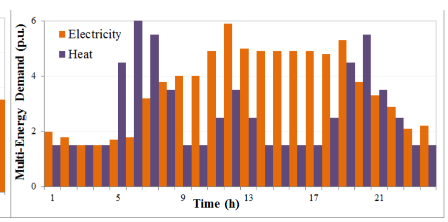

Fig. 6. Multi-energy demand data

Two case studies have been produced to demonstrate the role of PIEVs' PL in the SMES operation. The first case is SMES normal operation without PL and the second one considers the stochastic model of PL. Furthermore, some results for showing the effectiveness of stochastic model and the comparison with deterministic one are reported. The case studies results depicted in Fig. 7.

Figure 7.(a) to 7.(c) show the results of first case study for input gas to SMES and multi energy electricity and heat supply mixture. As it can be seen, CHP unit produce between 7-12 and 17-22 hours while EDS electricity price is high and also MED has the simultaneous heat and electricity consumption. Furthermore, HS has stored exceeded energy of CHP in 9, 10, 18, 21, and 22 hours when the EDS' price is high and CHP generation is profitable; however, MED has low heat usage which can be

solved by utilizing HS. These stored energy are given back to the SMES during 6, 13, 15, and 23 hours while the price is high and HS operation is more economical.

Figures 7.(d) to 7.(f) depict second case results which have considered the PL impact in operation of SMES elements. Figure 7.(d) shows less variation in output of CHP unit in hours 9-14. In these moments, PL as a stochastic storage enhances flexibility of the SMES and compensate the need for CHP variation by storing and injecting energy. Figures 7.(e) and 7.(f) demonstrate MED's electricity and heat usage; during low energy price (13-16), PL stores energy for injecting to SMES during peak period (18-21).

The SMES buys electricity from the PL in 12 mu/p.u. and sells it to PL in 10 mu/p.u. Therefore, it will be profitable for SMES operator to trade electricity with PL when the selling price is higher than EDS price and the buying price is lower than EDS price. As it can be seen in Fig. 7.(g), PL's SOC is less than scenarios amount between 9-13 and 18-21 and is more than scenarios amount between 14-17. In first discussed periods the electricity price is high and PL behave like storage and inject the energy to the SMES but in second period (14-27) the electricity price is low and PL behave as a manageable load which consume electricity to charge its PIEVs. Finally, in Fig. 7.(h) and 7.(i) the difference between stochastic and deterministic modeling for stored energy in HS and PL is depicted. The energy have been injected to the PL while the energy price is low for two reasons, first charging departed cars and secondly storing for consuming in peak hours. For the second reason, as a result of uncertain behavior of PIEVs, if operator charges the PIEVs' batteries and the PIEV departed from PL, operator miss part of its stored energy in PIEVs (PIEV's SOC) as loss. Therefore, as it can be seen in the stochastic case, the stored energy in PL is less compared to deterministic case because less stored energy means less loss and operation cost. However, less utilization of PL leads to more utilization of CHP which will result in more stored energy in HS (Fig. 7.(i)).

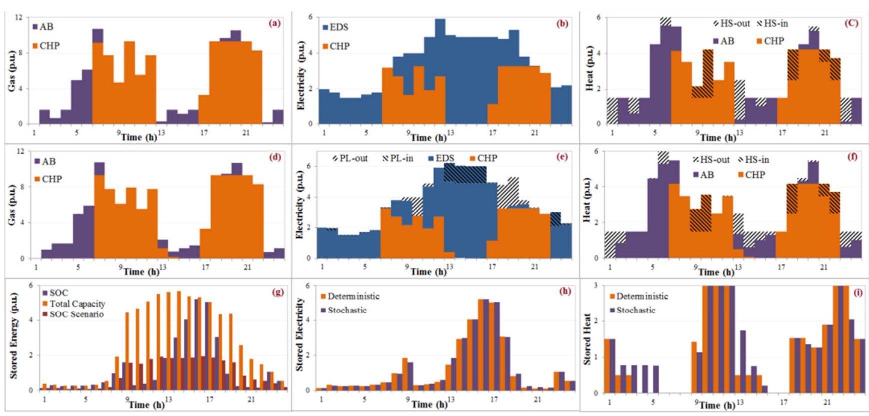

Fig. 7. Result of the proposed framework, (a) input gas without PL, (b) MED electricity consumption, (c) MED heat consumption mixture without PL, (d) input gas with PL, (e) MED electricity consumption mixture with PL, (f) MED heat consumption mixture with PL, (g) total capacity and SOC for PL during operation period, (h) stored electricity in PL for stochastic and deterministic case studies, (i) stored electricity in HS for stochastic and deterministic cases .

6. Conclusion

This paper proposed a framework for modeling PIEVs' parking lot in SMES operation. The model considers the behavior of parking lots as storage and flexible loads dependent to the upstream network price. Stochastic approach is employed to consider uncertainties around traffic pattern in parking lot. The numerical results have showed parking lot change the SMES elements' operation condition and prepares more flexibility for SMES to deliver requiring services. Furthermore, comparing stochastic and deterministic results demonstrates more information for the operator to utilize SMES elements which resulted in less operation of parking lot and more operation of CHP and AB.

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Appendix: SMES Elements' Characteristics and Nomenclature

Table1. Data of SMES elements' characteristics.

CHP Unit			Auxiliary Boiler		Heat Storage		
Output Energy (Min/Max)	η_e^{CHP}	η_h^{CHP}	Output Energy (Min/Max)	η_Q^{AB}	γ_Q^{HS}	Stored Energy (Min/Max)	$\eta_{Q,ch}^{HS}, \eta_{Q,dis}^{HS}$
0/5 pu	0.35	0.45	0/10 pu	0.9	3 pu	0.5/3 pu	0.9

Table 2. Definition of subscripts, parameters, and variables.

Subscripts					
W	Electricity	G	Gas	Q	Heat
s	Scenario	t	Time	Sc	Scenario
Parameters and Variables					
E	Energy stored	η	Efficiency	G	Gas consumption
Q	Heat output	W	Electrical power	Cap	Parking lot total capacity
L	Energy demand	λ	Heat to power ratio	π	energy carrier price
γ	Maximum charge and discharge rate of heat storage	$\dot{\mathbf{e}}$	(column vector) changes in stored energy	$\dot{h}$	Heat storage level difference in two consecutive time intervals
An underlined (overlined) variable is used to represent the minimum (maximum) value of that variable. Capital letters denote parameters and small ones denote variables.					